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Modeling Transpiration from Selected Urban Shade Tree Species[1]

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Abstract

A computer model of transpiration from individual tree crowns was modified, tested and verified using container-grown Norway maple (*Acer platanoides*) and sugar maple *(Acer saccharum),* two widely planted street trees in the Northeastern United States. Within each species, three soil moisture regimes were established to simulate non-drought stressed, moderately drought stressed and severely drought stressed conditions. Model estimates of transpiration were compared to lysimetric determinations as a verification of the model's ability to simulate the transpirational process. Model estimates of average hourly transpiration rates ranged from 6.8 to 55.5 g/m^2/hr (0.24 to 2.00 oz/yd^2 of leaf surface/hr) while lysimetric determinations ranged from 10.4 to 63.4 g/m^2/hr (0.37 to 2.28 oz/yd^2 of leaf surface per hour). The success of the model as a mechanistic simulation of transpiration, its areas of weakness and the need for further research to strengthen the model are discussed.

Index words: computer modeling, transpiration, *Acer saccharum,* sugar maple, *Acer platanoides,* Norway maple

Introduction

The benefits of trees and other vegetation in urban and suburban areas has long been intuitively accepted (14), but the empirical data to either verify or refute intuition have been lacking. If trees are indeed "nature's air conditioners," how much benefit can be expected to be derived from their presence in the landscape? We need to know the role vegetation plays in the overall urban and suburban energy budget to assess its amenity value in those settings.

The characteristic of the "urban forest," as it is called, is the lack of surface homogeneity of its vegetative cover. Due to this inhomogeneity, any study of the vegetative modification of the urban physical environment must consider the system at the level of the individual elements (7). Mechanistic modeling of the transpirational process of individual trees, however, allows for analysis of system function while arriving at estimates of transpirational water use and plant energy exchange.

Of more direct practical application for the nursery industry is the model's use as a predictor of the transpirational water use of individual trees. Any species/cultivar or size of tree under any set of environmental conditions can be simulated by the model, assuming some basic information is available for the plant. The model's output would be very useful in irrigation planning, both in the landscape and in production.

Past efforts in the modeling of transpiration have been directed primarily toward the development of canopy models (3, 5, 16, 17). There has not been a comparable effort in the development of models for trans-

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piration from individual tree crowns. There are several reasons for this, with the leading one being the inherent difficulty in modeling a system as complex as an individual tree crown.

The objective of this study was to update, test, and verify an energy balance crown model of transpiration developed by Welles and Norman (unpublished study). The model results were compared with measurements of tree water status parameters as a check of the model's ability to mechanistically simulate water relations. Model estimates of water use and measured values of tree water status parameters are reported here, as well as a discussion of the model and its characteristics.

Materials and Methods

Six trees each of *Acer platanoides,* Norway maple, and *Acer saccharum,* sugar maple, approximately 1.3-2.0 m (4-6 ft) in height were planted in 75 l (20 gal) trash cans, using a screened (13 mm or 1/2 in) silt loam soil conforming to the specifications of the Syracuse, NY street tree planting contract in effect at that time. Three water regimes were established within each species, with 2 replications of each: "wet"—soil water potentials greater than -0.1 MPa (1 bar), "moist" (-0.5 to -1.0 MPa (-5 to -10 bars)), and "dry" (less than -1.0 MPa (-10 bars)). These water potential ranges have been reported as having little, moderate, and severe effect on transpiration, respectively (11, 12). Model function was tested on each tree while its soil water potential was within the designated range for that tree.

The following environmental, plant water status, and plant descriptive parameters were measured for input to the model:

—soil water potential
—soil surface temperature
—leaf temperature
—air temperature
—dew point temperature
—shortwave radiation (0.3 to 4.0 *u*m)
—photosynthetic photon flux density (0.3 to 0.7 *u*m)
—wind speed
—crown dimensions
—Leaf azimuth and inclination angle distributions
—mean and total leaf area.

In addition, leaf resistance to water vapor diffusion and leaf water potential were measured as a means of assessing the model's capability as a simulation of the transpirational process.

Soil water potential determinations were made using Wescor PCT 55-15 ceramic cup soil psychrometer/hygrometer sensors connected to the Wescor HR33-T microvoltmeter. The sensors were inserted into the soil at a depth of 15 cm (6 in) and a radial distance of 15 cm (6 in) from the base of the tree. These sensors allowed measurements of soil water potential below 0.1 MPa as well as thermocouple measurements of soil temperature. Soil water potential readings were taken at 0600 and 1800 hours EDT and the mean of the two values was taken to represent the average soil water potential for that day.

Soil surface temperature was assumed to be equal to air temperature under the growing conditions of this study. This assumption would be invalid under field conditions, and the use of infrared thermometry would be essential for this measurement.

Leaf temperature was measured with a Mikron 25 portable infrared thermometer. Four leaves were selected during each sampling period, two each within both the upper and lower portions of the crown. One leaf in each crown position was sunlit and one was not. The four values were averaged to determine a mean crown leaf temperature for the sampling period.

Air temperature was measured using a shielded copper-constantan (type T) thermocuple. Ambient air passed over this thermocouple on its way to a Cambridge model 990 thermoelectric dew point hygrometer for dew point temperature determination. Both air and dew point temperatures were measured on a Comark electronic thermometer, referenced to a distilled water ice bath. From the readings of leaf, air, and dew point temperatures, determinations were made of ambient relative humidity, leaf-air vapor pressure gradient, and leaf-air temperature differential.

Total shortwave radiation was measured with a 10 junction Eppley pyranometer mounted on a stand 1.5 m (4.5 ft) above the ground. The diffuse component of shortwave radiation was determined by shading the sensor head of the pyranometer from the solar disk for 20 seconds (instrument 95% response time = 18 seconds) and reading the resultant output of the instrument. The flux density of direct beam solar radiation was calculated by subtracting the diffuse component from the total shortwave flux density.

PPFD (photosynthetic photon flux density) was measured with a Lambda Instruments model LI-85 quantum sensor. Both total and diffuse readings were taken as above, with the direct component again determined by subtraction.

Non-directional wind speed was measured on a model RB-1X Hastings Air Meter with sensor probe N-7B attached.

Crown dimensions were measured with a meter stick for use in computing crown volume. The formula for computing the volume of an ellipsoid, $v = 4/3 \pi abc$, was used where a, b, and c are the lengths of the semi-axes of an ellipsoid.

Leaf aximuth and inclination angles were measured with a compass and a protractor-plum bob system, respectively. The respective leaf angle distributions were determined by sampling approximately 80 leaves per crown and plotting the resulting distributions. This enabled a check to be made of some basic model assumptions.

A LI-COR model LI-3000 portable leaf area meter was used for leaf area measurement. A random sampling of 30 leaves from each crown was measured and a mean leaf area was determined. This mean leaf area was multiplied by the number of leaves in the crown of each tree to arrive at total crown leaf surface area. Leaf area density for each crown was then determined by dividing total leaf surface area by crown volume.

The resistance to water vapor diffusion of the abaxial leaf surface of the hypostomatous maple leaves was measured with a Lambda Instruments model LI-60 diffusion porometer. The sensing head was shielded at all times during and between readings to maintain it as close to air temperature as possible and the leaf was

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shaded for thirty seconds prior to sensor attachment to ensure leaf-air temperature equilibration. Resistance measurements were taken at the same four crown positions used for leaf temperature measurements, and the four values were averaged to compute a mean leaf diffusion resistance for the crown.

In situ leaf water potential determinations were made with the Wescor L-51 sample chamber and the HR33-T microvoltmeter. The chamber was shielded during the 30 minute equilibration period following attachment to the leaf. Due to instrumentation limitations, only one leaf was sampled for water potential determination during each 1 hr sampling period. This leaf was selected from the upper portion of the crown, in a position facing the direction of the solar disk to ensure optimal radiation exposure and to provide a standard leaf sampling location.

Model Operation. This energy budget model computes crown water use by reconciling the energy budget equation for the tree crown:

$$R_{net} = H + C + \lambda E, \quad (1)$$

where R_{net} is the flux density of net all wave radiation incident on the leaves, H is the energy flux density lost from the leaves through convection, C is the energy flux density lost through conduction, which is minimal for a tree crown, λ is the latent heat of vaporization of water, and E is the mass of water lost via transpiration from the leaves. Metabolic energy and stored energy are considered relatively negligible (2) and are not included in these calculations. By rearranging the above equation to read:

$$\frac{R_{net} - H - C}{\lambda} = E, \quad (2)$$

the model can solve for the mass of water lost via transpiration.

The four major component sections of the model are listed and described below.

Data Input. Data input exists at two levels in the model program. Data characterizing both the tree and the site are input once early in the program. Site data include: latitude, longitude and solar declination, needed for calculation of solar position. Tree physical characteristics input include: crown dimensions, height of the crown above the ground, leaf area density, branch area density, average leaf diameter, soil emissivity, and leaf reflectivity and transmissivity in the visible, near infrared, and infra-red wavebands of radiation.

Hourly data inputs include air temperature, soil temperature, beam and diffuse PPFD (photosynthetic photon flux density), beam and diffuse short wave radiation flux density, ambient vapor pressure, and wind speed. These variable parameters characterize the physical environment within the crown for each sampling period.

Physical Calculations. The tree crown is subdivided into 33 units for modeling purposes. Within each of these subvolumes, hourly energy fluxes are calculated for both shaded and sunlit leaf surfaces. After the direct and diffuse radiation levels in the visible and near infrared wavebands are determined, the total shortwave radiant fluxes are calculated for each subvolume.

The flux density of thermal radiation emitted by an object is a function of the temperature of that object:

$$\phi = \epsilon \sigma T^4, \quad (3)$$

where ϕ is the flux density of radiation (Wm^{-2}), e is the emissivity of the object, equal to the absorptivity in the infra-red waveband, σ is the Stefan-Bottzmann constant 5.67×10^{-8} ($Wm^{-2}T^{-4}$) and T is object temperature (°K). For each crown subvolume, the total flux density of incoming thermal radiation is the sum of that incident from above and below. Part of the incoming thermal radiation is due to surrounding leaf surfaces and part is due to radiation from atmospheric sources (sky radiation), or in the case of greenhouse grown plants, from the greenhouse structure. There are equations for sky radiation based on atmospheric temperature and vapor density information (2), but this study used a variation of equation 3, assuming in this case T equal to the glass temperature in the greenhouse, with an emissivity of 1.0.

Net radiation for any subvolume is calculated as the sum of the incident flux densities of radiation in the three wavebands, minus the sum of that lost through reflection, transmission, and emission of radiation in each waveband. The calculation of this net radiation term is the objective of the physical section of the model because it both drives and is affected by the physiological section, as will be discussed later.

Physiological Calculations. This section of the model simulates the physiological response of the tree to the physical environment as detailed in the previous section. Leaf resistance to water vapor diffusion is represented as a function of leaf temperature, PPFD levels, and leaf water potential, similar to the functions outlined by Jarvis (9). Leaf diffusion resistance decreases as PPFD increases up to a saturation level, beyond which diffusion resistance remains at a minimal level, unless influenced by the other factors. The optimum leaf temperature for diffusion resistance is considered to be 25 °C (77 °F). The water potential response is a threshold response. Above some characteristic value, water potential has no effect on diffusion resistance. Below some characteristic minimum leaf water potential, diffusion resistance is at a maximum, i.e., the stomates are closed. Between these two values of water potential, diffusion resistance responds inversely to leaf water potential.

Leaf water potential itself is a function of soil water potential, plant water loss and the hydraulic conductivity of the soil-plant system. Soil water potential serves as the base value, the maximum attainable leaf water potential. As water is lost from the leaves in excess of soil water replacement, leaf water potential drops. Once leaf water potential is calculated for a sampling period, that value is utilized in the stomatal response function for that period.

Leaf temperature is affected by net radiant energy load, leaf water loss, and wind speed. The fact that leaf temperature is affected by water loss requires that an iterative procedure be used for returning to the physical submodels to reassess the resulting change in the convective and net radiative fluxes. These new physical conditions are then incorporated into a new set of physiological calculations, and the process continues until the

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energy budget equation is reconciled, with energy inputs to the crown balanced by energy losses.

Output. Following a summary of static site and tree conditions, hourly energy and water use tables are output for both shaded and sunlit leaf surfaces. These hourly tables are broken down by sampling subvolume and include the physical and physiological conditions for each subvolume's shaded and sunlit leaf surfaces. The hourly output ends with a listing of: both latent heat and convective energy use for that hour, transpirational water use for that hour, and cumulative transpirational water loss for the day. This information is output for the number of hours specified in data input.

Results and Discussion

Lysimetrically determined transpiration rates for sugar maple agreed reasonably well with the results of Kozlowski *et al.* (10). No such basis for comparison could be found for Norway maple, so the lysimetrically determined transpiration rates for that species are assumed to be valid, based on the sugar maple results (Table 1). Of the ten trees studied, five showed model results within 30% of lysimetrically determined transpirational water use, one was within 35%, and four were over 50% in error (Table 1). All three trees in the "wet" woil moisture range, and two in the "moist," showed agreement within 30%, while the three "dry" and the remaining two "moist" trees were above that value. It appears that the model functions best when the modeled trees are under relatively low levels of soil moisture stress.

In the cases where model estimates of water use agreed well with lysimetric determinations, the model displayed good mechanistic simulation capabilities (Fig. 1). In this figure it can be seen that the model estimate of hourly tree water loss followed the trend of the measured shortwave radiation over the day. As radiation increased, transpirational water loss estimates increased. Under these conditions of high soil moisture, leaf water potential tended to remain relatively constant throughout the day, although the model dampened the fluctuations seen in the measured time course. Both modeled and measured leaf-air temperature differential tended to follow the general trend of the shortwave radiation curve, with the model estimate appearing to dampen the fluctuations of the measured response curve. Finally, the curves for both the measured and modeled stomatal diffusion resistance were relatively flat, probably due to the lack of either soil or atmospheric constraints on the transpirational process.

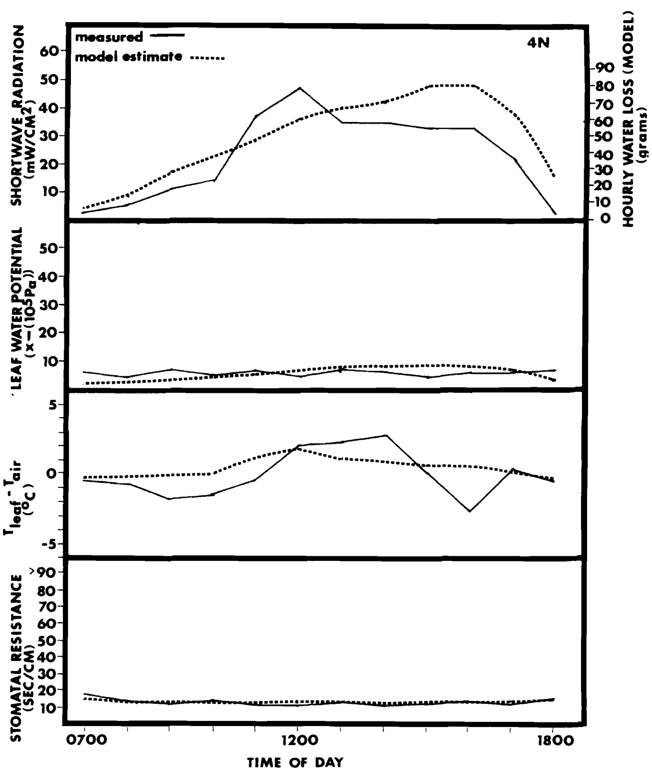

Fig. 1 Model estimates and measured water status parameters for a non-drought stressed Norway maple (soil water potential greater than -0.08 MPa).

When the two water use estimates did not agree, as occurred under conditions of soil moisture stress, model simulations of the physiological processes were not consistent with field measurements (Fig. 2). This figure shows the general correlation of water use estimates and shortwave radiation levels. In this case, the model overestimated water use by 88% (Table 1). Looking at the leaf water potential and diffusion resistance functions one can see at least part of the reason for this discrep-

Table 1. Summary table of model and lysimetric determinations of transpirational water loss.

Tree[z]	Soil (MPA)[y]	Leaf Area (m²)	Water Loss (g) Lysimeter	Water Loss (g) Model	Transpiration Rate (g/m²/hr) Lysimeter	Transpiration Rate (g/m²/hr) Model	% Diff. in Water Loss (M-L)/L
1S	-1.06(M)	0.884	280	256.5	28.8	26.4	- 8
4S	-1.70(D)	0.884	224	104.4	23.0	10.7	-53
5S	-0.08(W)	0.878	405	334.0	41.9	34.6	-18
6S	-0.91(M)	1.010	227	427.5	20.4	38.5	88
1N	-2.28(D)	0.804	260	116.2	29.4	13.1	-56
2N	-0.08(W)	1.203	508	660.0	38.4	49.9	30
3N	-0.87(M)	1.219	377	437.2	28.1	32.6	16
4N	-0.08(W)	0.886	618	540.9	63.4	55.5	-12
5N	-1.40(D)	1.751	200	131.6	10.4	6.8	-34
6N	-0.98(M)	1.092	371	602.0	30.9	50.1	62

[z] "S" Stands for Sugar Maple, "N" for Norway Maple.

[y] "W" = West, "M" = Moist, "D" = Dry Soil Moisture Condition.

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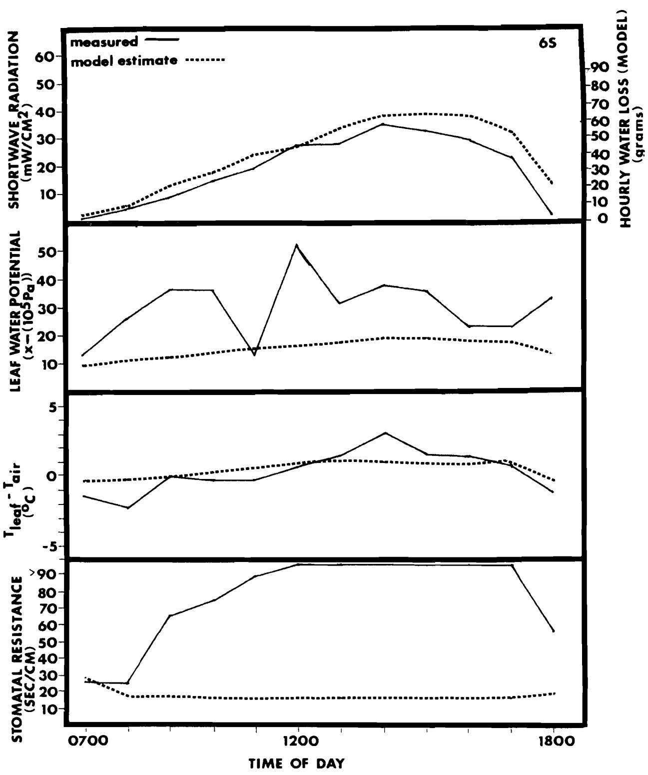

Fig. 2 Model estimates and measured water status parameters for a moderately drought stressed Sugar maple (soil water potential between -0.5 and 1.0 MPa).

ancy. The model did not account for the observed drops in leaf water potential and stomatal aperture during the day. Had these been reflected, the water loss curve at the top of the figure would not have continued to follow the radiation curve so closely over the day.

It was noted that the model's prediction and simulation performance was better at high soil water potential levels. With the variable nature of the soil/root interaction in terms of root water uptake, it is probably more prudent to work at high soil water potentials in the early stages of model development and testeing. This assumption may not be as restrictive for urban situations as one might initially be inclined to believe. The intuitive notion of the inadequacy of soil water supplies due to the widespread presence of paved surfaces in urban areas has not been borne out in the literature. An equally strong intuitive argument could be made against this notion by citing the amazing survival of trees under supposedly "hostile" urban conditions. There is so little known about the soil/root interactions, especially in urban areas, that this model should not even attempt to address the phenomenon at this stage. Working under optimal soil moisture conditions will lead to more effective model development. The following section details areas of the model in need of further developmental work.

Weaknesses in the physical submodels can be considered relatively minor in terms of overall model function. The leaf angle and area distributions within the tree crown need to be more accurately described. In addition, leaf optical properties in the various wavebands of radiation have been found to vary greatly among plants (1, 4, 5, 8, 13, 18). At this stage of model development, the first approximations used for these parameters are adequate, but sensitivity analyses will need to be run on the model at a later stage to determine their true effect on model output.

It appears that the simulative capabilities of the physiological submodels are more critical to crown model success (Fig. 1 and 2). Specifically, the simulations of the stomatal response and the leaf water potential response are currently not reliably adequate. The generalized stomatal response function used in the model cannot possibly represent all taxa under all conditions. In the instances where model estimates of leaf diffusion resistance approximated measured values (Fig. 1), model estimates of water use more closely matched lysimetric determinations than those instances where such approximations were not evident (Fig. 2). The lack of information existing on the stomatal response characteristics of individual taxa makes improvement of the model in this area quite difficult. By identifying this as a valuable and valid research area, perhaps a data base of such information can be developed.

Leaf water potential simulations present a similar problem within the model. Changes in leaf water potential result from the differential rates of transpiration and root uptake of soil water. A major factor affecting the change in leaf water potential over time is the hydraulic conductivity of the tree. Hydraulic conductivity, as used in the model, is the amount of water passing through a unit cross sectional area of xylem per unit of time per unit of potential gradient (Kg $m^{-2}s^{-1}(10^5Pa)^{-1}$). This is a flux density of water per unit potential gradient, and it differs from the conductivities reported by Heine (6) and Peel (15). The parameter needs to be determined experimentally for a range of taxa and the model adjusted accordingly as it is used.

The tree's hydraulic capacitance also affects water potential response due to differential rates of water loss and water uptake. It is widely known that tree stems shrink as transpiration proceeds in excess of soil water uptake (19), indicating that water is being removed from "storage" tissues to replace that lost through the stomata. The model's water potential response function currently does not include this potentially important factor.

We have succeeded in establishing the basis for further work in modeling of transpiration from individual tree crowns. The model is shown to be useful within a limited but practical soil moisture range, with potential for more widespread application. There are a number of areas of research that need to be explored to facilitate further development of the crown model. The most obvious need is the cataloguing of both stomatal response functions and leaf water potential response functions for a range of shade tree taxa. Much detail is needed this early in the model's developmental stage to allow it to be as true a simulation of the transpirational process as possible. Once the model is shown to be functioning properly, then attempts can be made to generalize and simplify the functions for application to a broader range of plant material.

There are other areas identifiable as research needs for model development. Such things as leaf optical properties and the seasonal and environmental effects

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upon them, the measurement of leaf angle and area distributions and their importance to model function, leaf area estimation in large trees and the effects of varying soil moisture stresses are all important to the model. As it develops further, these will be investigated and incorporated into a functioning crown model of transpiration.

Significance to the Nursery Industry

The theoretical aspects of the model are crucial to its continued development and improvement, but this work has some real and practical applications to the problems of landscape tree management. In addition to the use mentioned above, i.e., in assessing the role of trees in climatic modification, model estimates of whole tree water use can be utilized in formulating irrigation strategies for landscape plantings. The water emergency conditions of the past several years in the New York metropolitan area have caused both nurserymen and landscapers to be more conscious of their irrigation practices. At this time there is not a great deal of information available regarding water use of individual trees in a landscape setting. As a result, state mandated water rationing plans that were assembled in response to the water emergency were greeted skeptically, but helplessly, by the nursery industry. This model and its results can begin to provide the information needed by the industry both to better manage their crops and to ensure equitable solutions to water rationing problems.

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